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AN INVESTIGATION OF FLAME ARRESTER CONTINUOUS BURN TEST PROTOCOLS

E.E. Dainty and G. Lobay

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An Investigation of Flame Arrester Continuous Burn Test Protocols

by

E.E. Dainty[1] and G. Lobay[2]

ABSTRACT

Part A of this paper consists of an investigation of the effect of velocity and mixture concentration on the time to flashback of flame arresters employing different types of flame arresting media. It was determined that propane-air mixtures in the vicinity of stoichiometric concentrations produced minimum times to flashback, and that velocity plays a major role in determining the time to flashback, as does the type of media used in the flame arrester. The heat distribution through a conventional flat-faced arrester element was found to be relatively uniform if the gas velocity distribution was accordingly uniform.

Part B of this paper analyzes four testing protocols in light of the findings of Part A. Conclusions were made that the protocols do not provide worst-case test conditions, do not provide a reliable indication of flame arrester performance, are not repeatable, and do not subject equitable test conditions to units from different manufacturers. General recommendations are made on how a flame arrester endurance burn test should be structured.

KEYWORDS: Flame arrester, endurance burn, detonation arrester

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INTRODUCTION

Flame arresters can play a key role in an overall industrial explosion protection strategy, along with other techniques such as purging, gas detection, inerting, and implementation of correct operating procedures. Typical applications include:

- tank vents, which are intended to prevent any flames occurring outside a tank from entering the tank vapour space;

- process heater air intakes, which are protected by flame arresters so that ingested flammable vapour-air mixtures are prevented from flashing back, and causing an external ignition;

- in-line flare stack protection, so that a loss of flow to the flare and subsequent flashback does not cause flame transmission to upstream equipment;

- marine vapour recovery systems, where flame arresters are used to prevent the transmission of flame through pipes forming part of a vapour recovery system.

Because users, manufacturers, regulatory agencies, and other interests require a quantification of the minimum level of performance afforded by these devices, there has recently been an increasing amount of national and international interest in the development of flame arrester performance standards. Performance standards allow for the equitable application of a set of performance tests which provide baseline performance data that can be used as part of an acceptance regime.

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There are two general performance aspects involving combustion which must be addressed in any general flame arrester performance standard: continuous burn performance and explosion performance. Explosion performance deals with the ability of a flame arrester to prevent the transmission of a relatively rapidly-propagating deflagration or detonation combustion wave from its unprotected side to its protected side. These tests have a duration of considerably less than one second. Continuous burn testing, on the other hand, deals with the effects of a flame which can be considered as having stabilized at an arrester element and continues to burn, as a result of the gas flowing through the unit continuously providing adequate fuel for combustion to continue for minutes, or even hours. There have been reported instances of continuous burn situations leading to explosions at various industrial locations.

In either case, the intent is to assess these units so that a given level of performance can be determined for the product in these situations. This paper concentrates on the general area of continuous burn testing.

The first part of this paper (Part A) provides a description of continuous burn tests that were performed on flame arresters, the results obtained, a discussion of the mechanisms involved, and some conclusions concerning continuous burn performance. The second part of this paper (Part B) provides an analysis and discusses the technical validity of United States Coast Guard (USCG) continuous burn requirements, as stated in the United States Federal Register, Volume 55, No. 120, dated June 21, 1990, Appendices A and B to Part 154, in light of the findings described in Part A of this paper.

In addition, an analysis is provided of International Maritime Organization (IMO) document MSC/Circ.373/Rev.1, entitled "Revised Standards for the Design, Testing and Locating of Devices to

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Prevent the Passage of Flame into Cargo Tanks in Tankers", as well as on a proposed sixth edition for Underwriters' Laboratories document UL 525 "Flame Arresters for Use on Vents of Storage Tanks for Petroleum Oil and Gasoline".

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PART A - The Continuous Burn Mechanism

1. Objectives

The overall objective of this work is to further a general practical understanding of the flame arrester continuous burn mechanism.

The specific objectives of this work were as follows:

- determine how gas velocity through a flame arrester affects continuous burn performance;
- determine the effect of fuel-air mixture concentration on continuous burn performance by performing tests with lean, stoichiometric, and rich mixtures at a given velocity;
- obtain temperature profiles during burn tests to indicate temperature trends at key measuring points throughout the test;
- determine whether flow interruptions could cause failure prior to failure in the steady-state case;
- compare test data for various media types;
- make visual observations;
- arrive at some general conclusions about burn testing.

2. Introduction

A flame arrester can be described as a device which connects one vapour space with another, and which allows gas or vapour flow,

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but which has a certain level of capability to prevent the transmission of flames in at least one direction. Flame arresters may be in-line devices to prevent a flame from propagating any further down a piping system, as in the system feeding a flare stack, or it may be a venting device such as a vent installed on the top of a fuel tank which prevents external flames from propagating into the vapour space inside the tank. There are many thousands of such devices in use today, with increasing numbers being installed in vapour recovery systems as a result of environmental legislation limiting the discharge of vapours into the atmosphere.

Internally, flame arresters typically consist of some type of porous media, through which gas can flow. The media affords some measure of heat extractive capability and flame quenching by cooling, which in turn prevents flame propagation.

Although there are several different types of media, all of them have the characteristics of porosity and some measure of ability to absorb and dissipate heat; the essential flame-quenching mechanism in all of them is the same. The media breaks the single gas stream flowing into the flame arrester into numerous smaller gas streams as it passes through the unit, and by breaking the gas flow into small streams, achieves efficient intermixing and cooling of the combusting gas with the media, which in turn can cool and extinguish the flame.

If the gas stream in an in-line flame arrester system is ignited on the unprotected side, and the flame travels back to the flame arrester element, the single flame in the gas stream will be broken into numerous small flamelets when it reaches the media. These small flamelets will then continue to burn at the arrester element if the gas flow velocity and heat output are sufficient to overcome the quenching effect of the media on the flame. If the conditions of mixture concentration and flow velocity are

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suitable, the flame may stabilize and continue to burn for minutes, or even hours at the arrester. Eventually, if these conditions persist, flame arresters can fail, allowing flames to be transmitted to protected side equipment.

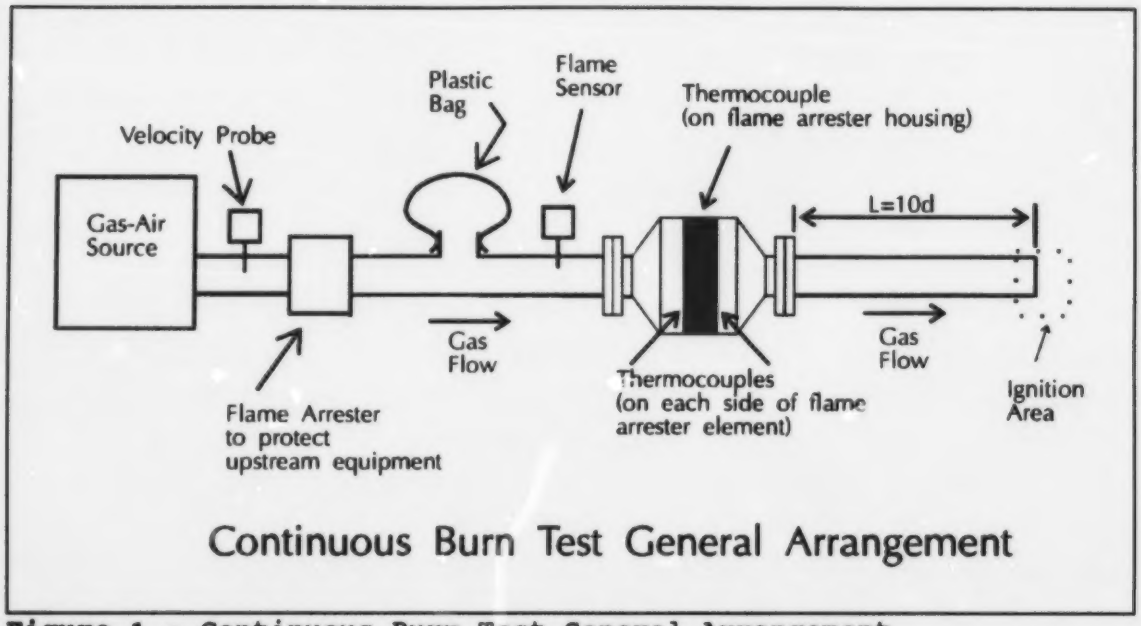

Figure 1 - Continuous Burn Test General Arrangement

3. Test Description

3.1 Test Arrangement

To further investigate the mechanisms of a continuous burn, the test arrangement shown in Figure 1 was used for several tests, carried out under controlled conditions. These controlled conditions included:

- mixture concentration held constant, with a selected velocity for each test, to determine time to flashback as a function of velocity;

- velocity held constant, with a selected fuel-air mixture concentration for each test, to determine time to flash-back as a function of fuel-air concentration.

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The test arrangement is representative of a typical in-line application, as might be used in a flare or vapour recovery system, and as such, is representative of a large number of installations.

All tests were carried out with flame arresters intended for connection to 3" nominal diameter pipe systems.

The air supply was derived either from a compressor for low flow velocities, or from a centrifugal blower. To obtain the homogeneous explosive gas-air mixture, propane was injected into the compressed air flow, or into the blower housing. Air flow from the compressed air supply was regulated by a rotameter, and air flow from the blower was regulated by means of a damper on the inlet to the blower. Propane flow was controlled by a rotameter. The gas concentration was analyzed by means of a calibrated Beckman Model 864 infrared analyzer, by continuous sampling of the gas stream just upstream of the flame arrester.

Velocities were measured by means of an anemometer with its probe inserted into the gas stream. The probe was protected from explosion by means of a protective crimped metal ribbon flame arrester inserted into the gas stream, ahead of the flame arrester being tested.

To detect flame transmission to the protected side, an infra-red optical spark and flame detector was installed on the protected side of the pipe, in addition to a plastic bag. In the event of flame transmission, the bag could be observed to explode, and the recording equipment which was connected to the optical detection equipment indicated flame detection.

Various thermocouple arrangements were used to determine temperature profiles and progression of heat through the flame arresters tested. All the thermocouples were type "K" units, connected via

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suitable thermocouple-to-voltage amplifiers to a continuous recorder. Usually, temperatures at three thermocouple locations were recorded simultaneously.

3.2 Test Procedure

Before conducting a burn, the optical detector was checked for correct operation, and a plastic bag was installed as shown in Figure 1 (page 6).

The gas mixture and flow velocity were established and verified with the appropriate instrumentation. Then, the gas exiting the pipe at the unprotected end was ignited by means of an electric spark. If the gas flow velocity away from the flame arrester was less than the burn-back velocity toward the arrester, the flame immediately travelled back to the flame arrester. In most cases, audible resonance of the unprotected side pipe occurred for at least the first few minutes of the test. Under steady-state flow and mixture conditions, the unit was allowed to burn until flashback was detected on the protected side. After flashback, the propane gas flow was cut off, but air was allowed to continue flowing to permit quicker cooling in preparation for the next test.

If, after ignition, the flame burned at the end of the pipe on the unprotected side and did not flash back to the arrester, the velocity was temporarily reduced so that the flame could flash to the flame arrester element. Once the flame had travelled back to the flame arrester, the test velocity was restored to the original value. Most conventional units have a flame arrester element surface area that is considerably larger than the pipe cross-sectional area. The gas velocity at the element surface is correspondingly reduced, which accounts for the fact that the flame remains positioned at the element surface, even when the velocity is restored to the original value. This situation could

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occur in field conditions where there is a momentary reduction in flow velocity which would allow a flame to flash back and be "trapped" at the arrester due to the increase in diameter and/or element surface area. In order to cause the flame to move away from the element surface, the velocity would have to be increased considerably. It would, however, be relatively difficult to stabilize the flame at a location other than at the thermal equilibrium position. This is discussed later.

3.3 Types of Units Tested

Extensive tests were done on three flame arresters, each of which employed a different type of flame arrester media as the element. One of the types was a conventional, commercially available, non-detonation arresting (i.e. the unit had no special features to prevent detonation transmissions), spiral-wound, crimped stainless steel ribbon flame arrester intended for use in 3" pipe applications. The other two units, also intended for use in 3" pipe systems, used very different media, although further details cannot be provided for reasons of confidentiality.

4. Velocity Effects

4.1 Velocity Variation Tests

In each of these tests, a flame was established at the arrester element at a maintained gas velocity and allowed to burn until flashback to the protected side was detected. It should be noted that as the element material heats during the test, some units exhibit a significant increase in back pressure, so a correspondingly higher pressure at the gas source is required to maintain the gas velocity at a constant level. The gas used was 4.2% propane (C.P. Grade) in air. The results of the tests are summarized in Table 1.

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With reference to "Unit ID" of Table 1, each unit employs a unique media, with the "A" unit being a conventional crimped stainless steel ribbon flame arrester, as identified in Figure 2. As stated above, the media in the other units cannot be identified.

Velocity (fpm)	Time to flashback (minutes)	Unit ID	Comments
50	41	A	
100	20	A	
150	12	A	
200	9	A	
200	10	A	Vertical flame arrester axis.
200	10	A	Momentary flow interruption at 8 minutes. No flashback on interruption.
250	6	A	
700	9	A	
1000	16	A	
1000	16	A	Vertical flame arrester axis. Red hot stack.
100	120	C	Test was terminated at 2 hours with no flashback.
200	120	C	Test was terminated at 2 hours with no flashback.
400	120	C	Test was terminated at 2 hours with no flashback.
170	87	B	
200	62	B	
300	47	B	
300	46	B	
450	48	B	

Table 1 - Effect of Velocity - Continuous Burn Test

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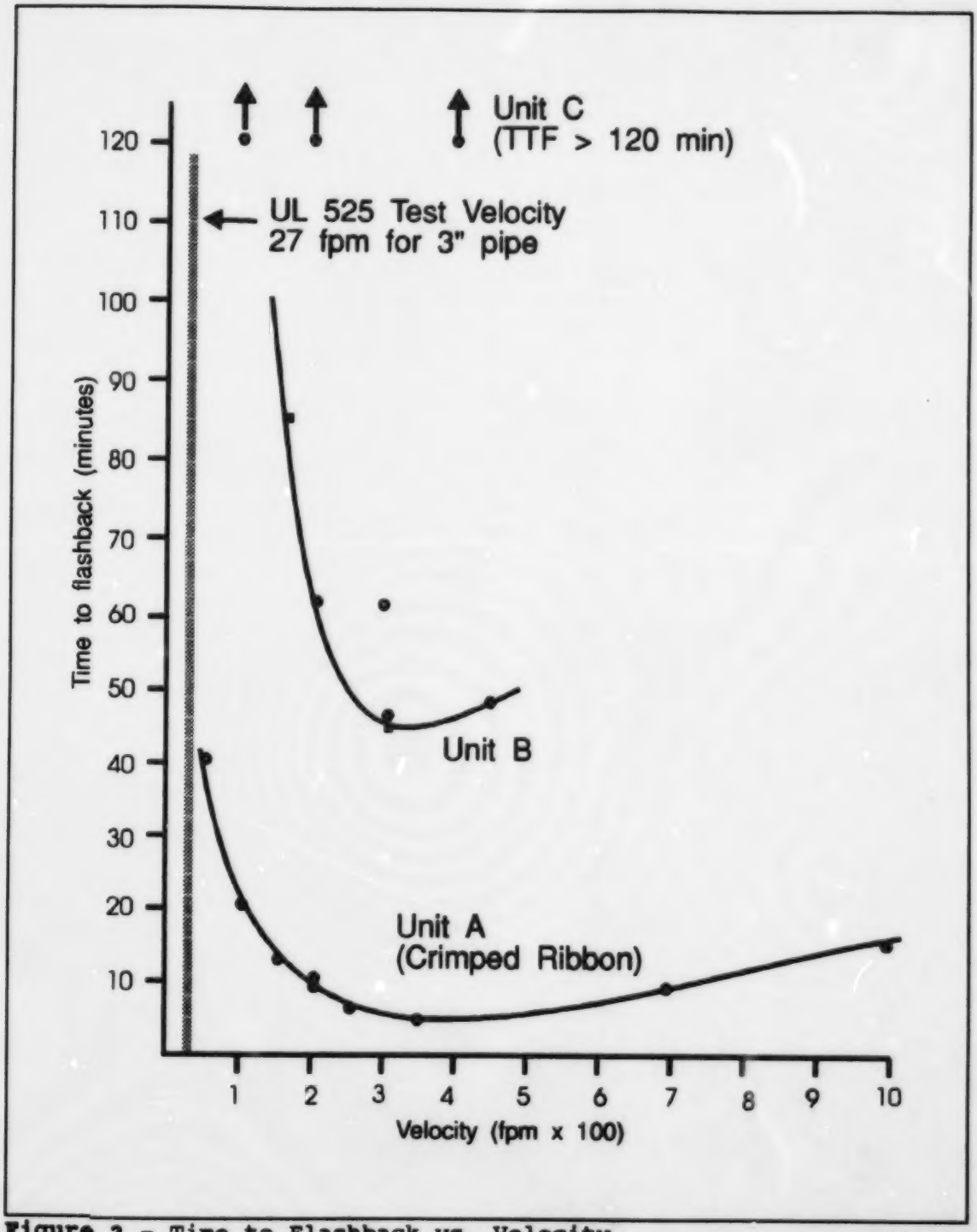

Figure 2 - Time to Flashback vs. Velocity

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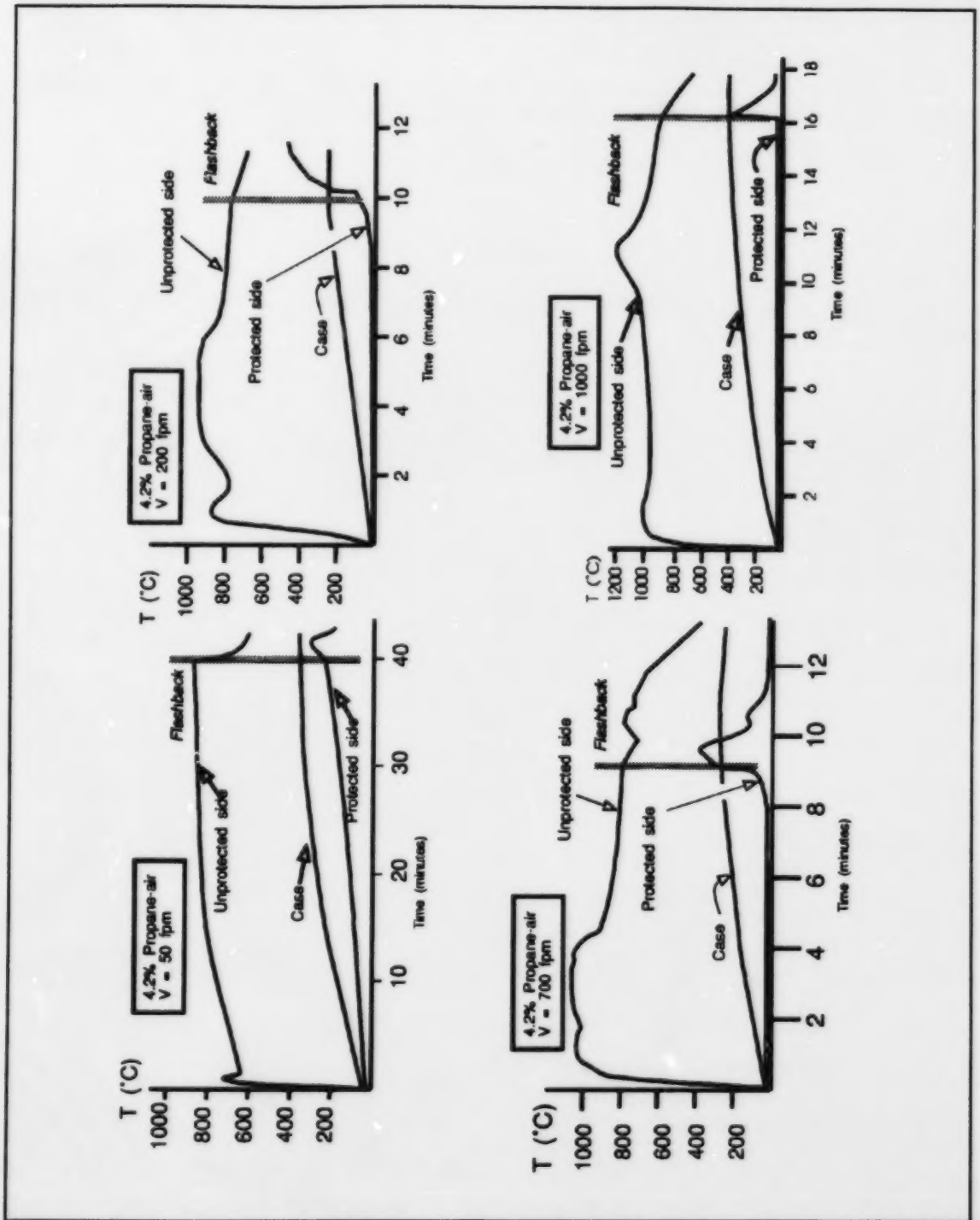

Figure 3 - Element and Case Surface Temperatures, 50, 200, 700 and 1000 fpm

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The results of Table 1 are plotted in Figure 2 (previous page). For the sake of comparison, the test velocity specified in UL Standard 525 for a 3" pipe flame arrester is indicated on the graph. It should be remembered that UL 525 does specify gasoline-air should be used as the fuel-air mixture, whereas all the data shown in Figure 2 were obtained with propane-air mixtures. Since the amount of heat liberated by combustion in a given time with a stoichiometric gasoline-air mixture would be somewhat greater than the heat liberated by a stoichiometric propane-air mixture, one would expect with gasoline-air vapour to obtain slightly reduced times to failure at any given velocity, relative to the propane-air mixture being used in these tests.

Clearly, if the test velocity is increased beyond a certain point, the time to flashback increases, in spite of the fact that the heat input to the system is greater. The reason for this is the increased gas velocity has the effect of "pushing" the hot zone of the stationary flame front away from the protected side of the flame arrester element. Thermal coupling between the element and the flame is less efficient, and more time is required to transfer enough heat to the element to raise it to a sufficiently high temperature to cause flashback.

As noted for the higher velocities in Table 1, the unprotected side pipe was observed to be red hot, as was the unprotected side pipe reducer, and yet the time to flashback had a higher value than at lower velocities, where no components were observed to be red hot. Furthermore, at higher velocities, an "organ-pipe" effect was responsible for a loud howling noise produced by the system, which might lead some to believe a very severe situation was in effect. This indicates that what <u>may</u> outwardly appear to be a more severe condition is in fact <u>not</u> the most severe test velocity.

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4.2 Surface Temperature Measurements

Three thermocouples were used in the tests of clause 4.1 to determine temperatures at the element surfaces and the exterior of the unit. Representative results of some of these measurements for one crimped metal ribbon unit are shown in Figure 3 (previous page), for velocities of 50, 200, 700 and 1000 fpm, respectively. One thermocouple was located at the unprotected side surface of the flame arrester element, at 75% of the element height. Another thermocouple was similarly located at the protected side of the flame arrester element. The thermocouples at the element surfaces were in contact with the media material. A third thermocouple was located on the flame arrester housing, so that the external temperature (the case temperature) could be measured.

The following observations were noted:

- the general trend of the traces remains the same, regardless of velocity. The length of the trace varies considerably with velocity, and there is some movement of temperature on the unprotected side in spite of the mixture and velocity being held constant throughout the test;

- on the unprotected side, the temperature at the element surface increases rapidly, which corresponds to its exposure to the flame which arrives and stabilizes initially at the element surface;

- for velocities in excess of 100 fpm, there is little or no increase of temperature from room ambient on the protected side, except for the period just before flashback;

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- the case temperature gradually increases over the entire duration of the test.

4.3 Internal Element Temperatures

Another series of tests was carried out to determine how velocity affected the progression of temperatures through the element of a standard crimped metal ribbon arrester element, as shown in Figure 4 and Figure 5. These thermocouples were thin units, which could be inserted into the channels of the arrester element at different depths. The positioning of the thermocouples is shown in the figures below.

Note that for Figure 4, where the velocity is relatively low, there is a less abrupt increase in temperature compared to the 200 fpm case (Figure 5), where the velocity is higher. This illustrates the cooling effect the incoming gas has on the element material. In the former case, there is more of an opportunity for the heat transmitted to the element material to be transmitted forward by conduction into the element material upstream of the flame area. In the latter case, the greater gas volume passing by the element material per unit time affords more of an opportunity for cooling of the element material to take place in this region. This is also illustrated in Figure 10 (Page 23).

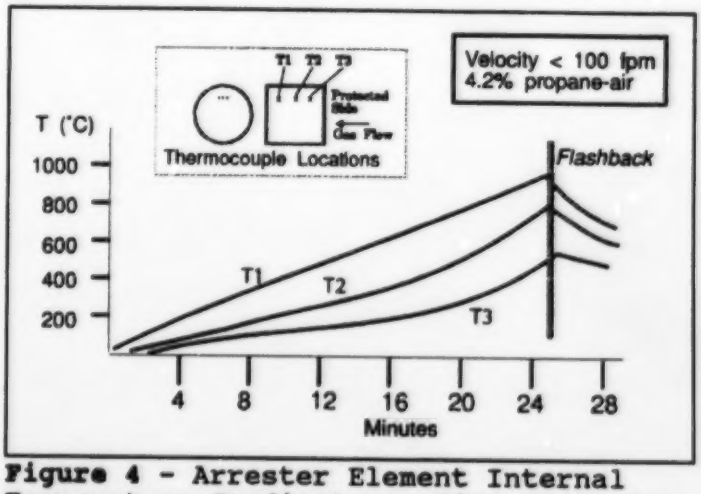

Figure 4 - Arrester Element Internal Temperature Gradient vs. Time at 50 fpm

The following observations were noted:

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- as time passes, the zone of high temperature widens, and progresses toward the protected side;

- the delineation between relatively cool and hot zones is a function of the velocity through the unit. Lower velocities tend to produce more uniform heating of the element, while higher velocities tend to produce a sharper distinction between these two regions, as shown in Figure 5.

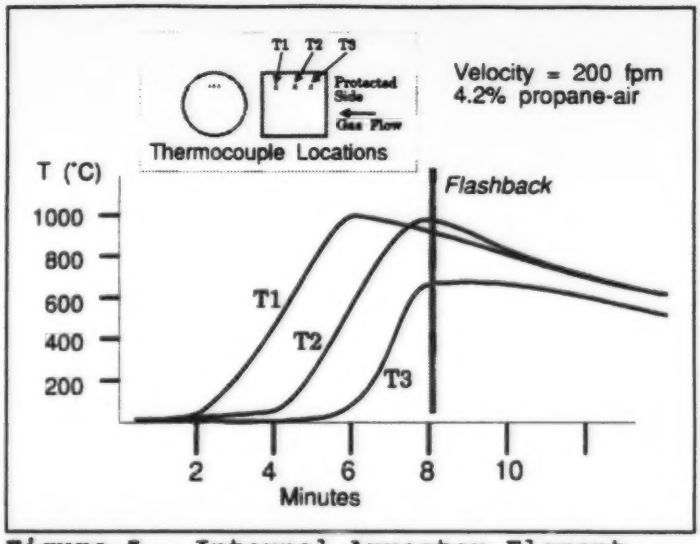

Figure 5 - Internal Arrester Element Temperature Gradient vs. Time, Velocity of 200 fpm

4.4 Radial Temperature Distribution

An investigation was also made of the radial temperature distribution over time within the crimped metal ribbon element, at a fixed distance from the surfaces of the element. Figure 6 shows that internally, the element temperature increases uniformly for this type of element geometry and test velocity, except towards the end of the test, as flashback approaches. As expected, the internal areas of the element that are most insulated from heat-absorbing surfaces, are the ones that ultimately see the higher

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temperatures. The rate of cooling provided ahead of the flame front would have an increasingly important effect as velocity increases.

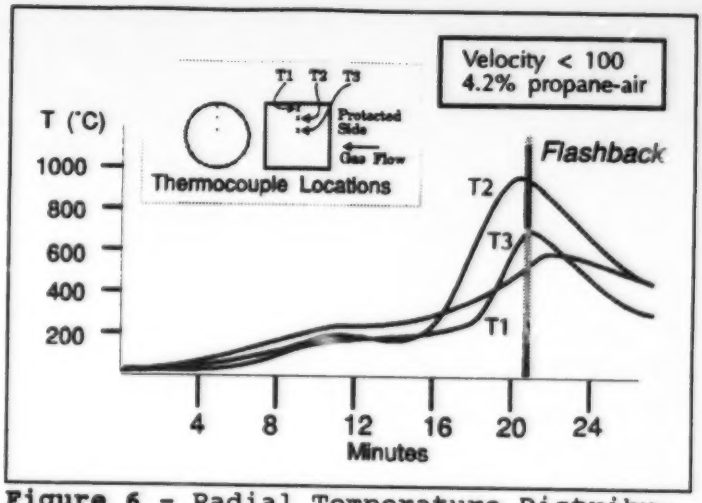

Figure 6 - Radial Temperature Distribution vs. Time

The radial distribution of temperatures throughout the element at any given axial distance tends to be uniform, with some depression due to heat sinking effects produced by the case of the arrester element, and by the central core of the element.

5. Visual Observations

For these tests, the reducer between the flame arrester element and 3" pipe on the unprotected side was removed from a standard crimped metal ribbon unit, so that the unprotected side of the flame arrester element would be visible at all times for observations. A flame was established at the arrester element, using a 4.2% propane-air mixture, at 200 fpm. The characteristic blue flame distributed itself uniformly over the entire area of the element. The visible combustion zone was less than one inch in thickness. After a few minutes, the element became red hot, and at the same time the flame gradually disappeared into the element. It was clear combustion was taking place inside the element media, since temperatures were being maintained, and the unit did flash back, as usual. As expected, the outer edges of the element and the central core, each of which is more closely coupled to a thermal heat sink, were last to turn red, and the element was observed in general to be uniformly heated.

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6. Effect of Fuel-Air Concentration

In these tests, the velocity was held constant at 200 feet per minute. Mixtures from 3.0% through to 6.0% propane-air were used in a number of tests with a crimped stainless steel ribbon arrester, and time to flashback was determined for each of the mixture concentrations. Clearly, the data in Figure 7 show that shortest times to flashback are obtained with fuel-air mixtures that are somewhere near to stoichiometric concentrations.

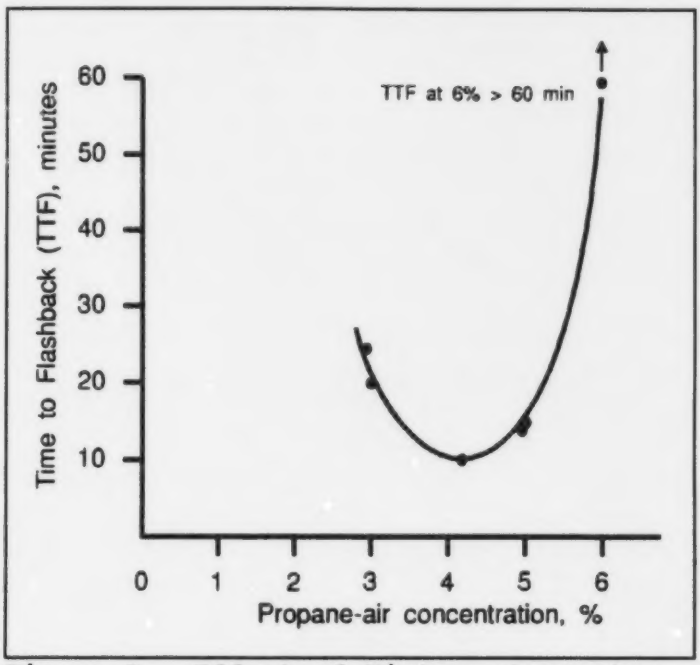

Figure 7 - Effect of Mixture Concentration on Time to Flashback for a Crimped Metal Ribbon Flame Arrester

Under stoichiometric conditions, all the fuel and oxygen is consumed. If the mixture is on the lean side, most of the fuel is quickly consumed, but less heat is liberated per unit volume of fuel-air mixture at the arrester element; in other words, although the oxygen is available, the fuel is not. On the other hand, if the mixture is rich, most of the oxygen is consumed, and the excess fuel is discharged along with the exhaust gas from the unprotected side pipe. Rich mixtures also burn more slowly, so the heat is less concentrated at the element surface. This was observed to be the case, since flames could be seen burning outside the unprotected pipe discharge of the test apparatus under rich mixture conditions, while high temperatures were at the same time being recorded by the unprotected side

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thermocouple. Reignition of the unburned portion of the fuel gas could be observed as the gas exited the unprotected side pipe. This broader combustion zone which rich mixtures produce makes it more likely for rich mixtures to be used in the endurance burn test (see Part B), since the requirement for stabilization of temperatures over a ten minute period can be more readily achieved.

7. Effect of Flow Interruptions

Flow interruptions were carried out during a number of tests, in the attempt to induce flashbacks. These interruptions were carried out as follows:

- as abruptly as possible, the flow of gas through the arrester was stopped;
- the flow was held stopped for 5 to 10 seconds;
- the flow was resumed through the unit, and the mixture was electrically reignited, if necessary. Reignitions were not always necessary, as in many cases there was enough residual heat in the arrester element available to cause the gas to reignite as soon as the flow was re-established.

It was only possible to obtain flashbacks by flow interruption if the interruption was carried out when the protected side temperature had begun its rapid rise, just prior to failure under the steady-state condition (see Figure 8).

8. Discussion

8.1 Applicability

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This discussion can be applied to units having a conventional flame arrester geometry where the element surface area is larger than the pipe cross-sectional area. In a conventional flame arrester, this usually means there will be a physical transition area having a gradual change in diameter, such as pipe reducer, enabling the pipe and arrester to be connected together.

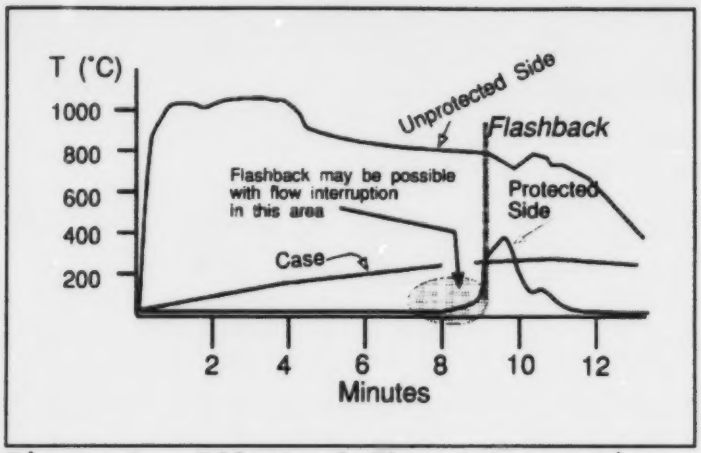

Figure 8 - Effect of Flow Interruption on Flashback

8.2 General Mechanism

The progressive burning of a stabilized flame through an element over time is in fact not much different in its mechanism from the manner in which a flame progresses, or propagates, through any fuel-air mixture in the deflagration mode. The difference, for the purposes of this discussion, is the rate at which the progression of the flame takes place. In the case of simple propagation of a flame front through a gas-air mixture (deflagration), there is much less heat dissipation (in other words, cooling) provided by the gas-air mixture for the flame front compared to the dissipation available in the porous metal media of a flame arrester. This being the case, the heating of the fuel-air mixture just ahead of the flame front (without a porous media hindering the rate of heating) is much more effective. The gas about to be consumed by the flame can be heated much more quickly to the point at which combustion can take place, and the velocity at which the flame front can propagate through the media is accordingly much higher. This dynamic equilibrium condition determines the rate at which the flame propagates through the

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material, and although there are many factors that determine the rate at which a deflagration-type flame front progresses though a given fuel-air mixture, the most significant factor for a flame arrester element is the degree of cooling that can be afforded by the porous media on the combustion that is taking place in, or on, the element media.

8.3 Conditions for Flame Quenching

Initially, the flame is established at the surface of the flame arrester element, and will persist for as long as the conditions of velocity and fuel-air concentration are suitable for combustion to occur. There must be sufficient heat released per unit time and per unit volume by the flame to overcome the quenching effect of the media, or otherwise the flame will be extinguished. A flame will not be produced if the gas velocity through the flame arrester is so low that insufficient fuel-air mixture can be delivered to the incipient flame front to satisfy the minimum requirement of heat released per unit time per unit volume, and the incipient flame will be quenched. Over time, if there is sufficient fuel delivered to the element, the flame will heat the element material, and may heat it sufficiently to overcome any flame quenching capability that the media may have had when it was cool. If this occurs, the flame quenching effect of the hot media will be lost, the flame will enter the media itself, and will burn within the media at an equilibrium point where the flame can just overcome the quenching effect of the media material. As more of the media is heated by conduction and radiation, the flame progresses further into the media, and the process repeats until the flame has worked its way nearly through all of the media, when it will suddenly flash through to the protected side. The sudden flashback is the result of more effective conductive heating of the media, as the hot zone of the media widens, and the quantity of cooler media decreases. When the remaining relatively cool media is heated sufficiently, the point will be reached where flame propagation all the way through

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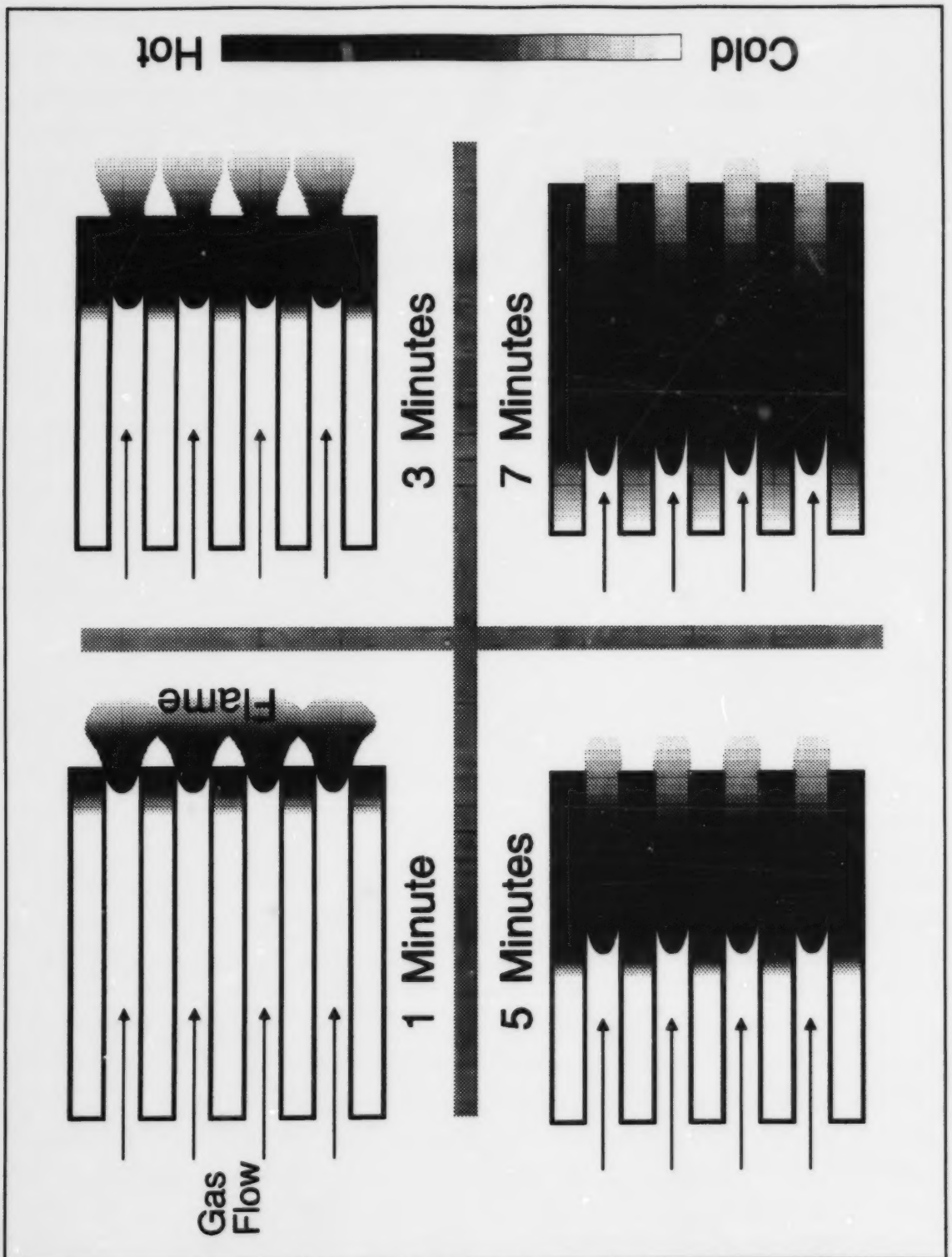

Figure 9 - Progression of Flame Through a Conventional Element

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the media to the protected side can be possible.

8.4 Heat Flux Through a Small Section of Media

As shown in Figure 10, unburned fuel-air mixture entering the element will tend to have a cooling effect on the media, although the flame arrester "hot zone", and the transition zone from cool to hot will widen over time, because the cooling provided by the unburned fuel entering the unit will not be sufficient to counteract the heat generated from combustion. In this illustration of a small section of the media, some of the heat from combustion will be transmitted to the metal material of the media; the heat will be dispersed by conduction through a portion of the metal that comprises the media, and will be cooled by the influx of unburned fuel-air entering the channel. The protected side element temperature will not show any upward trend until the unit is close to flashback. It is this cooling effect that is responsible for the temperature gradient through the element which is most noticeable at higher velocities.

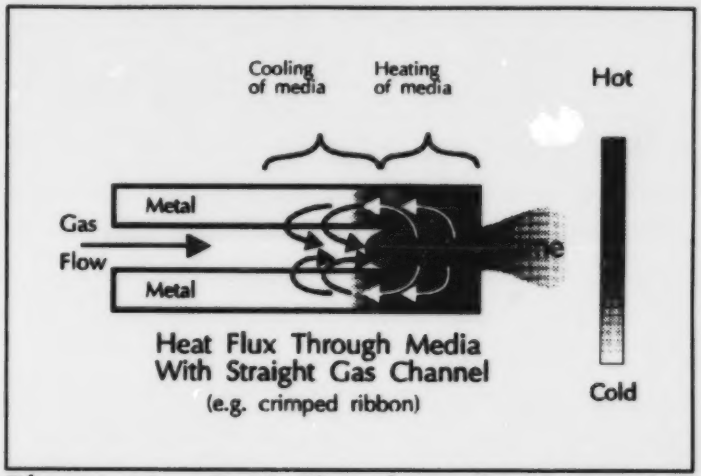

Figure 10 - Heat Flux in a Small Section of Flame Arrester Element

8.5 Flame Stabilization in Pipe Transition

Within the pipe-to-element reducer, there will be a profile of increasing velocity, in going from the larger-diameter flame arrester element to the pipe diameter. The distribution of velocities in the pipe reducer as shown in Figure 11 make it

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impossible for a flame front to stabilize in the reducer area (not impossible, however, for the trailing end of the flame to be present in that location). Since the flame tends to travel toward the element, the flame front will encounter decreasing gas velocities as it approaches the element, which means that it will accelerate toward the element face.

If the gas velocity is increased at the arrester element to the point where it overcomes the flame velocity and causes the flame front to move into the transition area from the face of the flame arrester element, the retreating flame will encounter an even higher velocity region and will accelerate away from the element, into the pipe, and out the end.

8.6 Flame Stabilization in Pipe

There is some need to point out the difficulty of maintaining the stable position of a flame front in a pipe. Although it would be possible to adjust the width of the "hot zone" through mixture and velocity adjustments, so there would be the appearance of stabilization of a flame at a given temperature measuring point, such would be not the case. This is borne out by how difficult it is to position a flame front in a pipe by adjusting gas velocity to just equal the flame velocity. Invariably when this is attempted, the flame will flash one way or the other, but will seldom if ever stabilize in a constant-diameter pipe. With reference to Figure 11, note that where the diameter of the pipe is constant, the

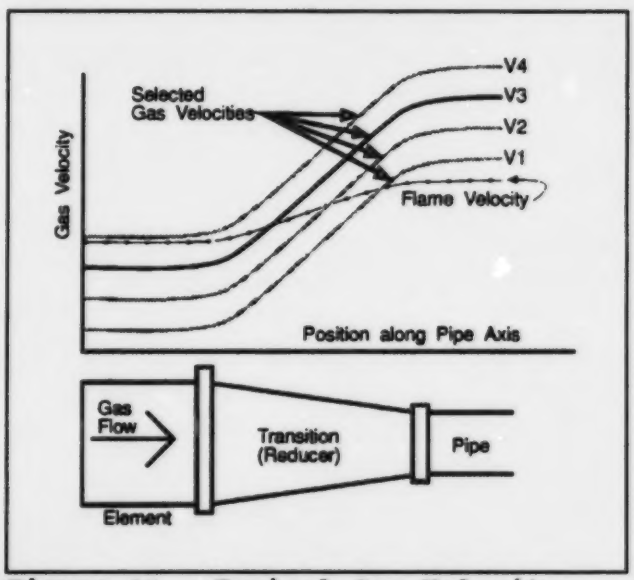

Figure 11 - Typical Gas Velocity Profiles Through Pipe Transition

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unburned fuel-air velocity and the flame velocity are constant values. The flame velocity can be characterized as a relatively constant value in this special situation, because a short, open-ended, straight piece of pipe, involved with "standing" combustion waves will not be as subject to the dynamic "pressure piling" effects that take place in more confined deflagrations. Accordingly, the gas velocity and the flame velocity values are represented by two parallel lines in Figure 11. If the gas velocity is adjusted so that it is equal to the flame velocity, the flame velocity will equal the incoming gas velocity over the length of the pipe, which remains an unstable situation, since there is no unique solution to this set of parameters. Also contributing to the difficulty of maintaining a "standing flame" in a pipe is the turbulence of the incoming gas near the walls of the pipe, which will cause the flame to have somewhat different localized velocities.

8.7 Heating of Transition Area and Unprotected Pipe

Although it would be very difficult to stabilize a flame front in the transition area or pipe, it is certainly possible to achieve significant heating of that area (to the extent where in some of the tests carried out in this report, these components became red hot) because at higher velocities, the high-temperature zone broadens, especially with richer mixtures, so that flames may be present all through the reducer area and into the unprotected side pipe. The higher velocities also provide proportionally more energy per unit time to the combustion process, so more power is pumped into the system to provide a greater heating effect. At these higher velocities, the cooling effect by the unburned fuel gas passing through the arrester element is significant, and protects it from flashback in spite of the dramatic red-hot unprotected side components. The cooling is effective to the extent that this is not as severe a condition as is produced in lower-velocity tests. Under these higher-velocity conditions, the system is more likely to howl audibly as a result of pipe

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resonance effects. Figure 9 illustrates the typical progression of a stabilized flame through a conventional flat-faced arrester element over a period of time.

8.8 Are These Worst-Case Test Conditions?

Ideally, the design of any testing protocol would simulate absolute worst-case field conditions, so that any possible field condition would be less severe, and product performance could be assured under all conceivable circumstances. However, flame arresters are subject to an infinite variety of ever-changing flow velocities, gas concentrations, combinations of gases and other factors, all of which contribute to some degree of uncertainty with respect to how the product would perform in an actual application. It is not possible to design a testing protocol that would simulate all these conditions.

In fact, the conditions of constant velocity and gas mixture are not worst-case conditions for some units. It is possible to adjust velocity and mixture test conditions during a laboratory test to cause a flame arrester to flash back in less time than it would take under conditions of steady-state mixture concentration and gas velocity. The problem with trying to incorporate this approach into a testing protocol is that the equatability of application of the test criteria would be very difficult to maintain, since considerable experimentation would be required to determine the absolute worst-case conditions for that unit. Still, those would only be the worst-case conditions for that particular gas, which might not produce a worst-case scenario for some other gas, or mixture of gases, being used in the field.

The better approach is to arrive at a set of test conditions which can be relatively easily reproduced and carried out, which would provide a reliable indication of performance under known test conditions, and which would account for a large portion of anticipated field conditions. Since all units would be subjected

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to exactly the same test conditions, this information could be used to compare the burn test performance of one unit with another.

9. Conclusions

9.1

If the velocity through the element material is low enough, and if the mixture concentration is correct, a flame can stabilize at the arrester element, heat the element media, and if the heat absorbtion rate of the element cannot keep up with the heat output, the flame can progress through the media until a flash-back point is reached.

9.2

The time taken from the start of a flame stabilization at a given arrester element to flashback for a given fuel is a function of the velocity through the unit, the mixture concentration, the thermal mass of the media used for the flame arrester material, and the ability of the element to dissipate the heat it has absorbed.

9.3

The optimum fuel-air mixture for minimum time to flashback is close to stoichiometric concentrations for propane-air mixtures, e.g. from 3.7% to 4.7% propane in air by volume. It is likely a similar conclusion could be applied to other fuels.

9.4

Since the minimum time to flashback for a given flame arrester will be a function of velocity, it would be necessary to test the unit at a number of burn test velocities to determine the performance characteristics of the unit. The single test velocity of the UL 525 standard shown in Figure 2 illustrates how incom-

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plete (and possibly misleading) the information produced by one burn test at one velocity can be.

9.5

At higher velocities, protected side temperatures do not rise above the temperature of the gas stream flowing into the flame arrester until just before flashback occurs, and may not rise at all, until after flashback. Lower velocities produce a gradual increase in protected side temperatures over the duration of the test. Protected side temperatures do not "peak" until after flashback has occurred.

9.6

The temperature distribution at the surface of a flame arrester will correspond to the velocity profile of the gas flowing through the element, assuming uniform heat dissipation around the circumference of the unit. For a flat-faced element, where the gas flow is more or less uniform over the surface of the unit, the heat will be uniformly distributed over the face of the element.

9.7

With velocity and gas concentration held constant, the unprotected side temperature, measured at the surface of the element, does vary over time due to the changing heat absorbtion dynamics of the unit under test, as shown for the various velocities in Figure 3.

9.8

The observation of dramatic physical effects, such as portions of a flame arrester becoming red hot, or howling noises, must not be interpreted as being the worst-case test conditions for a flame arrester. Typically, for a test that produced the minimum time to flashback for a given unit in this report, no portion of a unit became red hot (as observed in a well-lit room), nor did it

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produce any howling noises during the burn (except for a few moments at the start of the test).

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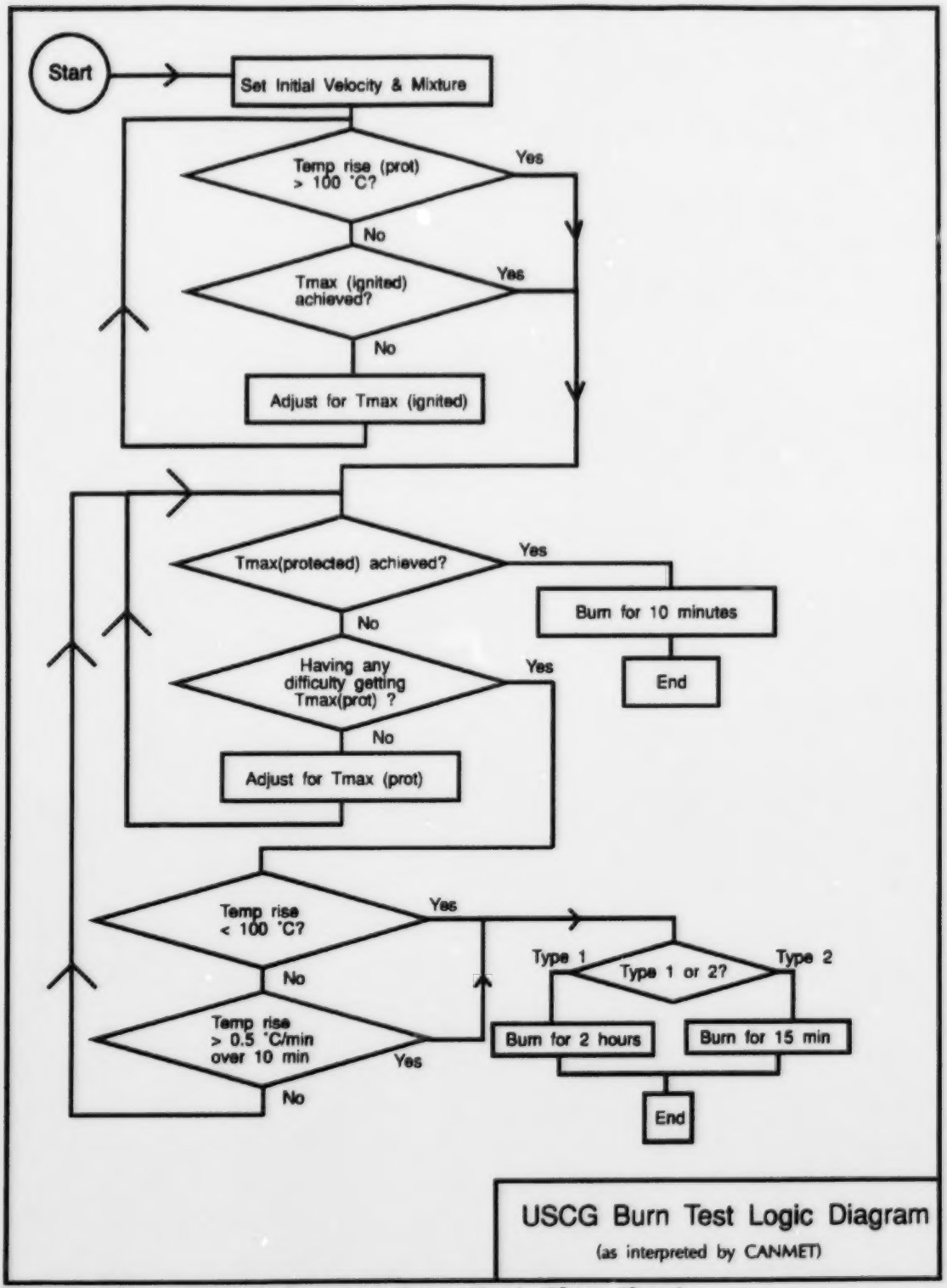

Figure 12 - USCG Endurance Burn Test Flow Chart

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US COAST GUARD ENDURANCE BURN TEST PROCEDURE FOR FLAME ARRESTERS

14.2
Endurance Burn Test Procedure

14.2.1
An endurance burning test shall be carried out as follows:

14.2.1.1
The test rig shall consist of an apparatus producing an explosive mixture, a small tank with a diaphragm, a prototype of the detonation flame arrester and a firing source in close proximity to the test device (see Figure 1). The detonation flame arrester shall be installed so that the mixture emission is vertically upwards, or installed in the position for which it is designed and which will cause the most severe heating of the device under the prescribed endurance burn conditions. In this position the mixture shall be ignited.

14.2.1.2
Endurance burn test shall start by using the most easily ignitable test vapour/air mixture with the aid of a pilot flame or a spark igniter at the outlet. The flammable mixture may be reignited as necessary in the course of the endurance burn.

14.2.1.3
Temperature measurement will be performed on the surface of the arrester element half way between the centre and its edge.

14.2.1.4
By varying the proportions of the flammable mixture and the flow rate, the detonation flame arrester shall be heated by a stable flame on the surface of the arrester until the highest obtainable temperature is reached on the ignited side or until the temperature on the side which was not ignited (protected side) rises 100°C.

14.2.1.5
The flammable mixture proportions will then be varied again until the conditions which result in the highest temperature on the protected side are achieved. This temperature shall be maintained for a period of ten minutes, after which the flow shall be stopped and the conditions observed. The highest attainable temperature is considered to have been reached when any subsequent rise of temperature does not exceed 0.5 °C per minute over a ten minute period.

14.2.1.6
If difficulty arises in establishing the highest attainable temperature on the protected side, the following criteria shall apply. When the increase in temperature on the protected side occurs so slowly that its temperature does not rise 100°C, the conditions which produced the highest temperature on the ignited side of the arrester will be maintained for two hours. For the condition in which the temperature on the protected side continues to rise at a rate in excess of 0.5°C per minute for a 10 minute period, endurance burning shall be continued, using the most severe conditions of flammable mixtures and flow rate, for a period of two hours. In either of these cases, at the end of the two hour period, the flow shall be stopped and the conditions observed. The two hour interval shall be measured commencing with the setting of the conditions which produced the most severe conditions of mixture and flow rate. For Type I detonation flame arresters, flame passage shall not occur during this test. For Type II detonation flame arresters, the maximum temperature obtained, and the time elapsed from the time when the most severe conditions are set to when flame passage occurs, shall be recorded. However, for Type II detonation flame arresters the test may be terminated 15 minutes after setting the most severe conditions on the protected side.

Text of the USCG Endurance Burn Test Requirements

PART B

1. Objective

The objective of this part is to provide an analysis, in light of the findings in Part A of this report, of the following test protocols:

- United States Coast Guard (USCG) Standard endurance burn test, as stated in United States Federal Register, Volume 55, No. 120, dated June 21, 1990, Appendices A and B to Part 154, clause 14.2 (Appendix A) and clause 14.3 (Appendix B);

- International Maritime Organization (IMO) document MSC/Circ.373/Rev.1 "Revised Standards for the Design, Testing and Locating of Devices to Prevent the Passage of Flame into Cargo Tanks in Tankers", clause 3.2.3;

- Underwriters' Laboratories document UL 525 "Flame Arresters for Use on Vents of Storage Tanks for Petroleum Oil and Gasoline", clause 7;

- Underwriters' Laboratories draft proposal for a sixth edition of UL 525 dated October, 1991, clauses 8 and 14.

Users may be depending on regulatory-agency-accepted products as having a certain minimum level of endurance burn performance. What is that minimum level of performance? The above requirements are analyzed so that a clearer picture emerges of how the minimum performance levels set by these requirements are linked to actual flame arrester endurance burn performance characteristics. The intent of this analysis is to place more information into the hands of users, who can then use that information as an aid to making safety-related decisions.

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2. USCG Requirements

2.1 Introduction

The USCG endurance burn tests are intended to apply a set of performance test criteria to detonation arresters, and form part of an acceptance regime administered by the US Coast Guard for those devices. Most interest has been focused on the detonation testing aspects of the USCG requirements, and much has been said about what is not in those requirements (e.g. the "momentum effect"). This paper deals with the technical validity of the approach taken in the USCG requirements with respect to endurance burn testing, as specified in clause 14.2 of the USCG requirements, and again, what is not in that document as it relates to endurance burn testing. Underwriters' Laboratories, in their proposed testing requirements for detonation arresters, bases its proposed endurance burn test on principles similar to those implemented by USCG.

Any acceptance regime such as the above must be based on a reasonably sound technical foundation. The tests must be defined in such a way that they are able to be interpreted and applied equitably, regardless of what laboratory is doing the test, and must yield consistent results.

This paper attempts to interpret the USCG requirements of Appendix A, and analyzes those requirements in light of the findings in Part A of this report. Since the USCG Appendix B requirements for endurance burn testing of tank vent flame arresters (i.e. non-detonation) are virtually identical to the IMO requirements, the reader is referred to the commentary on the IMO document below for a discussion on that subject.

2.2 Analysis And Discussion

Page 31 provides a reproduction of the actual USCG test requirements, and page 30 provides an interpretation of the USCG test

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requirements in flow-chart form. The requirements can be interpreted as having two main components, which are to:

- set flow and mixture conditions to obtain maximum temperature on the unprotected side; then,

- readjust mixture and flow conditions to obtain maximum temperature on the protected side.

There are no time constraints specified in relation to the above determinations.

The approach of this analysis will be to look at the individual statements in the schematic and comment, based on the results presented in Part A of this report.

2.2.1 Analysis of USCG Clause 14.2.1.4

Clause 14.2.1.4 of the USCG requirements states:

> "By varying the proportions of the flammable mixture and the flow rate, the detonation flame arrester shall be heated by a stable flame on the surface of the arrester until the highest obtainable temperature is reached on the ignited side or until the temperature on the side which was not ignited (protected side) rises 100°C."

The difficulty with attempting to maximize the temperature on the ignited side is that as the maximization process proceeds through variation of gas velocity and concentration, the element itself is being heated by the test flame. As the element becomes heated, there is a good possibility for the test flame to enter the element material, as explained in Part A. If this happens when the test gas is stoichiometric or leaner, the temperature measuring device at the arrester element will begin to experience

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a drop in temperature, since it will be exposed to hot products of combustion exiting the element, which are not as hot as the flame itself. This can be seen in Figure 3 (page 10) where there are variations in the temperature over time as measured at the unprotected side of the arrester.

If the attempt is made to maximize the temperature when there has been a reduction in temperature due to the flame entering the element, this would require an increase in gas velocity through the element, or gas mixture enrichment in an attempt to bring the hot zone back to the measuring point.

If the velocity were to be increased, a very substantial increase in velocity would likely be required to push the hot zone back to the thermocouple, since the heated element material would at that point afford no flame quenching capability. It would also probably be very difficult to maintain the flame position at the arrester element, since there would no longer be a thermal equilibrium point at the hot face of the arrester element.

Increasing the velocity has been shown in Part A to generally reduce the severity of the test, which is contrary to the objective of producing the most severe test condition. The severity is reduced because the amount of direct thermal contact of the flame with the element material is reduced.

Another approach to maximization of temperature on the unprotected side would be to make the fuel-air mixture rich, which has the effect of broadening the combustion zone. Although this would provide apparently good temperature stabilization, the work in Part A indicates that rich mixtures allow much longer times to flashback.

The USCG requirements are silent at this point about what criteria are to be applied in determining whether a maximum tempera-

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ture value has been achieved. It could be assumed that the clause 14.2.1.5 criterion of temperature rise not exceeding 0.5 °C/minute over a 10 minute period applies to this clause, although the document is not explicit in this respect.

For those units that have a large thermal mass which prevents entry of the test flame into the arrester material during the temperature maximization period, it would be easier to produce the required maximum temperature condition, since the flame would stay in position over the unprotected side thermocouple relatively longer, while the maximization was being carried out.

It would be difficult for the above step to be applied in an equitable manner from one unit to another. Depending on the thermal behaviour of the arrester element, significant variations in test severity would be experienced by different units, especially if different conditions of velocity and mixture were established for each unit. Since the USCG standard specifies no time window during which the maximization must be made, this portion of the test becomes that much more vague and subject to interpretation. The test could have considerably different outcomes depending on how long a period is allotted by the test agency in its search for maximum flame temperature.

The USCG requirements appears to be premised on the concept that the flame stabilizes at the element surface and remains there for any given time; it seems to be expected that the flame remains in position while the temperature is being maximized. In fact, the work in Part A has shown that this premise is incorrect. For at least two types of media, and quite possibly another type of media which has not yet been tested by this laboratory, the flame actually enters the media. This false premise makes it difficult, if not impossible, to equitably apply the USCG requirement for maximization of temperature from unit to unit, since each

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testing agency will use its own unique approach in attempting to maintain maximum temperature on the unprotected side.

The second part of clause 14.2.1.4 provides an alternative to maximization of temperature on the unprotected side. It allows for this portion of the test to be exited if the temperature rise on the protected side is greater than 100 °C. As determined in Part A of this report, there is usually no temperature rise on the protected side surface until the unit is very close to experiencing flashback, or the test velocity is very low. As such, temperature rise on the protected side is an unreliable indicator - this condition may occur early in a test, late in a test very close to flashback, or not at all, depending on how one chooses to do the test. Again, the application of this rule is inequitable from one type of unit to another.

Finally, is a "maximum" as defined in the USCG requirements, really a maximum? Figure 13 indicates a hypothetical protected side temperature trend, which is not far removed from a real-world low velocity flame arrester protected-side characteristic. In Figure 13, the temperature has stabilized for the required 10 minute observation period, and for the purposes of the USCG requirements, is to be interpreted as a maximum value. However, if the test is allowed to progress, the temperature then rises by an additional amount. The USCG

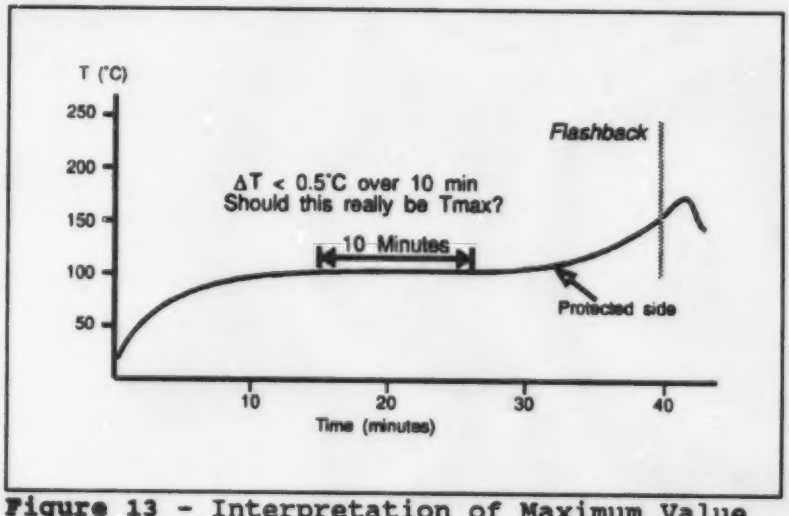

Figure 13 - Interpretation of Maximum Value as Described in USCG Requirements

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requirements seem to direct the testing authority to terminate the search for maximum as soon as the temperature stabilization over ten minutes has been achieved, which means that the real maximum has not been observed.

2.2.2 Analysis of USCG Clause 14.2.1.5

Clause 14.2.1.5 of the USCG Requirements states:

> "The flammable mixture proportions will then be varied again until the conditions which result in the highest temperature on the protected side are achieved. This temperature shall be maintained for a period of ten minutes, after which the flow shall be stopped and the conditions observed. The highest attainable temperature is considered to have been reached when any subsequent rise of temperature does not exceed 0.5 °C per minute over a ten minute period."

The second part of the USCG requirements shifts its focus to the protected side of the flame arrester. As stated above, under most conditions for conventional units, there is little or no temperature rise on the protected side of the flame arrester. There is a moderate increase of temperature on the protected side when the velocity is relatively low. In any event, the trend is always generally upward for the protected side temperature, as time goes on. As shown in Figure 13, there may be a halt for a period of time in the upward trend, which would later resume.

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In addition to the discussion above, the definition of "highest temperature on the protected side" also causes problems because the 10 minute time span for maximum value observation is very significant for some types of media, since under worst-case conditions of mixture and velocity, flashback has been seen in as little as 5 or 6 minutes.

Under high flow conditions, such as 1000 fpm, the maximum value criterion usually cannot be met, since the temperature rise on the protected side will most likely remain below 100°C. Clause 14.2.1.6 interprets a temperature rise of less than 100 °C on the protected side as being "difficulty", so that clause would have to be invoked.

How does the testing authority carry out the tests associated with this clause? Nowhere in the USCG requirements is there <u>any</u> suggestion that a test strategy involving a succession of tests such as were done in Part A of this paper be done. The inference is made that <u>one test</u> be carried out, in which parameters are varied to achieve maximum temperature on the protected side. However, it has been shown that only through a succession of tests, carried out under controlled conditions, that a picture emerges of the flame arrester endurance burn performance.

There is a possibility for a maximum temperature to be achieved on the protected side through mixture and flow control, although these mixtures and flows <u>would not be coincident with optimum flashback conditions</u>. If rich mixtures were to be used, heating of the element material could be carried out to demonstrate a maximum value on the protected side, and at the same time there would not be flashback due to the non-ideal nature of the gas mixture. The intent of the requirements would be satisfied, and "difficulty" would not be experienced. The conditions that produced the maximum temperature on the protected side would then

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be maintained for 10 minutes, as required in clause 14.2.1.5, and the test would be completed.

This demonstrates that the USCG requirements impose conditions which can be met in this regard, although the test conditions imposed by the requirements are far from being able to provide a complete safety assessment of the product. The USCG requirements give priority to the maximization of temperatures, at the expense of the other variables, which are mixture and velocity. Part A of this paper has shown that a systematic approach to velocity variation with a near-stoichiometric mixture will provide a far clearer assessment of the product.

2.2.3 Analysis of USCG Clause 14.2.1.6 ("Difficulty" Clause)

In light of the foregoing, it is likely that "difficulty" will very often be encountered.

The USCG requirements contain two implied definitions of "difficulty":

- the temperature rise on the protected side is less than 100 °C; or

- the temperature continues to rise at a rate greater than 0.5 °C per minute over a ten minute period.

The question also arises as to how long the testing authority is to keep attempting to achieve a maximum temperature on the protected side of the flame arrester. Again, as time progresses, the dynamics of the system are ever changing, and the flame arrester continues to be heated during the search for a maximum. This has an impact on the next phase of the test, in that some performance capacity for the flame arrester is lost due to heating during the search, penalizing the unit accordingly.

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At this point it should be mentioned that this is one of the key flaws in the protocol: Since there is no time limit set for the temperature maximization process (for either side of the flame arrester), various units will be subjected to various amounts of heating time during that process, which will accordingly place them on an inequitable basis for the ensuing Type I or Type II endurance burn. In fact, the situation is made worse since there is no control specified on mixtures or velocities during the temperature maximization process, which has a direct and very significant effect on heating of the arrester element, which in turn determines the remaining time to flashback for the unit. Again, this places different units on a playing field which most likely will not be at all level.

Once "difficulty" has been established, and at least one of the "difficulty" criteria has been met, the unit then has to be subjected to a burn test of either two hours or 15 minutes duration, depending on whether it is a Type I or a Type II unit.

At this stage, a sentence-by-sentence analysis is required.

> "When the increase of temperature on the protected side occurs so slowly that its temperature does not rise 100 °C, the conditions which produced the highest temperature on the ignited side of the arrester will be maintained for two hours."

As stated previously, this condition can be achieved, but in a typical scenario it will require that velocity constantly be increased to maintain the flame at the surface of the flame arrester element, and/or that the mixture be enriched. Increased velocity will contribute to more effective cooling of the arrester element and will prolong the burn time for the unit significantly. It will also be likely that rich mixtures will be

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used to maintain the maximum temperature, since the combustion zone for a rich mixture is broader, and will increase the width of the "hot zone" of the flame, which will provide more controllable heating of the thermocouple on the unprotected side of the unit. These do not reflect the conditions which minimize time to flashback, as shown in Part A, and could in fact be used for a contrary effect, namely to maximize time to flashback and/or prevent flashback from happening at all.

> "For the condition in which the temperature on the protected side continues to rise at a rate in excess of 0.5 °C per minute for a ten minute period, endurance burning shall be continued, using the most severe conditions of flammable mixture and flow rate, for a period of two hours."

In this sentence, the key phrase "<u>most severe</u> conditions of mixture and flow rate" is unclear as to <u>what</u> must be made "most severe". Is it to maximize the rate of temperature rise on the protected side? Is it to maximize the temperature on the unprotected side? Clearly, it cannot mean that one is to maximize temperature on the protected side, since the protected side temperature continues to rise, which is one of the "difficulty" conditions.

If the intent is to maximize the rate of rise on the protected side, low velocities would be used, since very low velocities produce the greatest rate of rise on the protected side. This condition is not the one which produces anything close to a minimum time to flashback.

If the intent is to maintain maximum temperature on the unprotected side, then as stated above, velocity will have to be increased and/or the gas mixture enriched as time goes on to

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maintain the condition, which again produces a condition which is also not close to minimizing the time to flashback.

> "The two hour interval shall be measured commencing with the setting of the conditions which produced the most severe conditions of mixture and flow rate."

The same questions concerning "most severe conditions" as stated above arise, in that the references are not clear. This sentence also attempts to add some equatability by specifying when the burn interval timing should start. Unfortunately, it fails to recognize the significant differences in heating that can occur from unit to unit when attempts are being made to maximize temperatures, prior to setting of the "most severe" conditions.

> "For Type I detonation flame arresters, flame passage shall not occur during this test. For Type II detonation flame arresters, the maximum temperature obtained, and the time elapsed from the time when the most severe conditions are set to when flame passage occurs, shall be recorded."

In the above passage, there is the implicit assumption that the most severe conditions (those of velocity and mixture) which produce highest temperatures, remain constant once they are "set". This is not always the case. For example, in order to maintain the highest temperature on the unprotected side, at least the velocity, and perhaps the mixture, will have to be adjusted significantly over the life of the test. The standard in this respect is impossible to fulfil, since it requires a "setting of conditions" to maintain the most "severe" conditions, whereas the reality is that the conditions have to be <u>varied</u> to maintain the most severe conditions of temperature at the face of the arrester element.

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> "However, for Type II detonation flame arresters the test may be terminated 15 minutes after setting the most severe conditions on the protected side."

Once again, the issue of what conditions are being made most severe, is called into question, and is discussed above.

Finally, this test protocol is written with the implication that one test be carried out, with mixture and flow being varied during that one test. The work in Part A has shown that the effect of mixture and/or flow adjustments is not reflected on the protected side temperature immediately, if at all. There is a time lag between cause and effect which will tend to severely mask any observable links between protected side temperature and mixture/flow adjustments. Since there is a unique set of mixture and flow test conditions that produces the shortest time to flashback, it is likely that the test conditions which have been set will not match these critical values as the user tries to maximize temperature on the protected side by varying mixture and flow. Accordingly, it is unlikely that minimum times to flashback will be produced using the specified method.

2.3 Scenarios

The purpose of this section is to illustrate how the latitude that is available in the USCG Requirements has an impact on the outcome of the tests that are carried out on one particular unit. These tests were not actually carried out, but represent plausible scenarios, based on the information presented in this report. Scenarios 1 and 2 were carried out in accordance with the USCG Requirements, Scenario 3 was not.

SCENARIO NO. 1:

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The testing agency could, through mixture and flow variations observe a 10 minute "maximum" temperature on the flame arrester unprotected side. As stated above, these have nothing to do with worst-case conditions. Having satisfied this, the flow velocity could then be greatly reduced, and the mixture controlled to allow conductive heating through to the protected side until at least a 100°C rise in temperature on the protected side was demonstrated, followed by a stabilization of temperature. This would satisfy all the conditions, and the test would terminate with a 10 minute burn under these low-flow conditions. Again, these conditions have nothing to do with worst-case conditions.

SCENARIO NO. 2:
The same unit could be subjected to a temperature maximization process on the unprotected side as in Scenario No. 1. Then, in spite of efforts to obtain a "maximum" on the protected side, the temperature rise does not exceed 100°C. This is "difficulty", so clause 14.2.1.6 would have to be invoked. With relatively high velocities and rich mixtures, the high temperatures on the unprotected side are maintained for at least 15 minutes as required by clause 14.2.1.6, and the unit would qualify as a Type 2 unit.

SCENARIO NO. 3:
The testing agency could take the same unit and subject it to real worst-case conditions of velocity and mixture, and have the unit flash back to the protected side in 10 minutes.

2.4 Conclusions

The following key assumptions appear to have been made in the design of the USCG requirements. All of these key assumptions are either totally or substantially <u>incorrect</u>, if <u>true</u> worst-case conditions are to be produced:

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Incorrect Assumption No. 1:
Determination of maximum attainable temperatures on the unprotected side surface of a flame arrester, and then on the protected side, are of primary importance for any unit; gas velocity and concentration are of secondary importance.

Incorrect Assumption No. 2:
A flame can be made to stabilize at the element surface. Once the conditions have been set for that to take place, conditions will remain constant such that the flame will remain in that fixed position for the duration of the test;

The work in Part A, and the discussion in Part B, clearly show that the above assumptions that were made in the design of the USCG requirements were incorrect. This leads to the following conclusions:

Conclusion No. 1:
If the USCG requirements are attempting to produce conditions which determine the minimum time to flashback for a given flame arrester, the requirements have failed to make this determination.

Conclusion No.2:
If the USCG requirements are attempting to set a minimum level of performance for flame arresters with a concomitant minimum acceptable level of safety, then they have failed to do this. Any units "accepted" by the USCG will have indeed met the requirements of the protocol to the letter, but the actual performance capabilities of these units under many endurance burn conditions remain **undetermined**. Such units may well be capable of flame transmission to the protected side in less than the minimum times allowable by the USCG standard.

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Conclusion No. 3:
If the USCG requirements are attempting to equitably apply a set of test conditions to all units, as they should, there is in fact an unacceptably low possibility for these requirements to be applied fairly. There is far too much latitude allowable for mixture and velocity variations, too much room for interpretation, too many incorrect assumptions made in the design of the protocol, for any of the requirements to be applied consistently to different units, or even repeatably to the same unit. It is not possible even to determine the degree of inconsistency involved with these requirements.

2.5 Recommendations

The USCG should commence a review process of its existing published flame arrester endurance burn requirements.

Any requirements for burn tests should involve known, controlled test parameters. The tests should be repeatable for the same unit, and should be equally applied to all units which become subject to the requirements.

Repeatability means that when a test result is produced, it is possible at a later date to test the same item under the same test conditions and produce the same result, within the bounds of reasonable error.

For a burn test to be applied equally for all units, the test conditions have to be independent of the internal construction of the unit, so that there is no functional relationship between the technology that is used in the flame arrester with the test methodology. In other words, there should be no linkage between how the test is performed with how the arrester is constructed internally.

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In view of the foregoing, and the information that has been presented in Part A, the following recommendations are made for endurance burn tests.

All the tests should be carried out at one gas concentration, namely the stoichiometric concentration in air for the fuel involved. The use of propane or natural gas is recommended, rather than hydrocarbons that are normally liquids at room temperatures and pressures (such as gasoline) because accurate mixture control is relatively more difficult for those substances due to vaporization and condensation problems.

A number of steady-state burn tests need to be carried out until flashback occurs. These must be done at various velocities, in order to determine the burn test characteristics for the unit under those conditions. The test conditions should include an adequate number of tests to develop a time-to-failure profile for the unit involved. For example, four or five burn tests, each conducted at a fixed velocity, using the fixed fuel-air mixture described above could be used. The test velocities, whatever they are determined to be, should represent values which cover most field applications as determined by industry surveys before being set down in legislation. The velocities should also be selected to take into account the range of flame arrester element surface element areas that are available from manufacturers. These fixed test velocities may be a function of pipe diameter.

For a 3" pipe, flames will not travel back to the flame arrester unless the test velocity is less than about 700 fpm (using 4.2% propane-air), and will burn at the open end of the unprotected side pipe attached to the flame arrester. If the test velocity is momentarily reduced, the flame will travel back to the element and stabilize there. Accordingly, test velocities should include these higher values, but the test protocol should provide for momentary flow interruptions to allow the flame to travel back to

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the arrester, after which the actual test velocity could be re-established. Momentary flow interruptions in actual field situations have been reported as being the cause of continuous burn situations at an arrester element, so some tests should be carried out at these higher velocities.

Each test should be carried out at the fixed velocity and fuel-air mixture until flashback occurs, or until a maximum time duration is reached, e.g., two hours. Temperature measurements are not used in any regulatory sense, but only to provide information to the testing agency about the progress of the test, and to provide a way to document the test.

Each of the tests yields a time-to-flashback value. These values would then have to be compared with whatever acceptance criteria had been established. One acceptance method might require a minimum time to flashback of 30 minutes for any of the test velocities for any unit. Another might assign a "rating" to the unit, based on the minimum time to flashback.

The acceptance scheme would have to take into consideration those technologies that prevent a flame from being established at the arrester element at any of the given test velocities, and not penalize the unit if it had such a capability. One such capability might be a fire extinguishing system that would be automatically triggered upon sensing heat at the element; another might be special geometry that did not permit flame to be established at the arrester element.

A regime such as this would satisfy the criteria for equatability and repeatability. These tests would not favour any one arrester element technology over that of another in that they would allow each unit for a given size of pipe to be subjected to exactly the same gross quantity of heat per unit time. The tests would be

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reasonably simple to do, and would be repeatable from one day to the next, and from one laboratory to the next.

These tests would not reproduce a worst-case test condition for a given unit, although by testing through a range of velocities as recommended, a reasonable and reliable assurance of a given performance level could be obtained.

3. IMO Endurance Burn Requirements

3.1 Introduction

The International Maritime Organization (IMO) is a technical organization, affiliated with the United Nations, which develops conventions, codes and recommendations for international shipping. These requirements are developed through the efforts of a number of IMO committees having representation from member countries. Although the IMO itself has no regulatory authority, some of its most important conventions are now accepted by countries whose combined merchant fleets represent 97% of the world total.

Requirements for flame arresters were developed under the direction of the Fire Protection Subcommittee, reporting to the Maritime Safety Committee, which in 1988 recommended that IMO member governments be "invited to give effect to these Standards". The requirements form part of MSC/Circ.373/Rev.1 "Revised Standards for the Design, Testing and Locating of Devices to Prevent the Passage of Flame into Cargo Tanks in Tankers".

3.2 Discussion of MSC/Circ.373/Rev.1 Clause 3.2.3

These requirements were published prior to publication of the USCG requirements; they follow one other closely with respect to test methods for non-detonation arresters. The test requirements are as follows:

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"Endurance burning shall be achieved by using the most easily ignitable gasoline vapour/air mixture or the most easily ignitable technical hexane vapour/air mixture with the aid of a pilot flame or a spark igniter at the outlet. By varying the proportions of the flammable mixture and the flow rate, the arrester shall be heated until the highest obtainable temperature on the cargo tank side of the arrester is reached. The highest obtainable temperature may be considered to have been reached when the rate of rise of temperature does not exceed 0.5 °C per minute over a ten minute period. This temperature shall be maintained for a period of ten minutes, after which the flow shall be stopped and the conditions observed. If difficulty arises in establishing thermal stability, the following criteria shall apply. When the temperature has reached the apparent maximum, using the most severe conditions of flammable mixture and flow rate, but increases at a rate in excess of 0.5 °C per minute over a ten minute period, endurance burning shall be continued for a period of two hours from the time the most severe apparent conditions have been established, after which the flow shall be stopped and the conditions observed. Flashback shall not occur during this test."

Figure 14 provides an interpretation of the IMO endurance burn test requirements in flow-chart form. In essence, the IMO requirements require a stabilized flame to be established on the unprotected side of the flame arrester, and that a ten-minute temperature maximum on the protected (tank) side be obtained. The IMO requirements differ from those of the USCG in that for the IMO tests, the temperature on the unprotected side is to be ignored.

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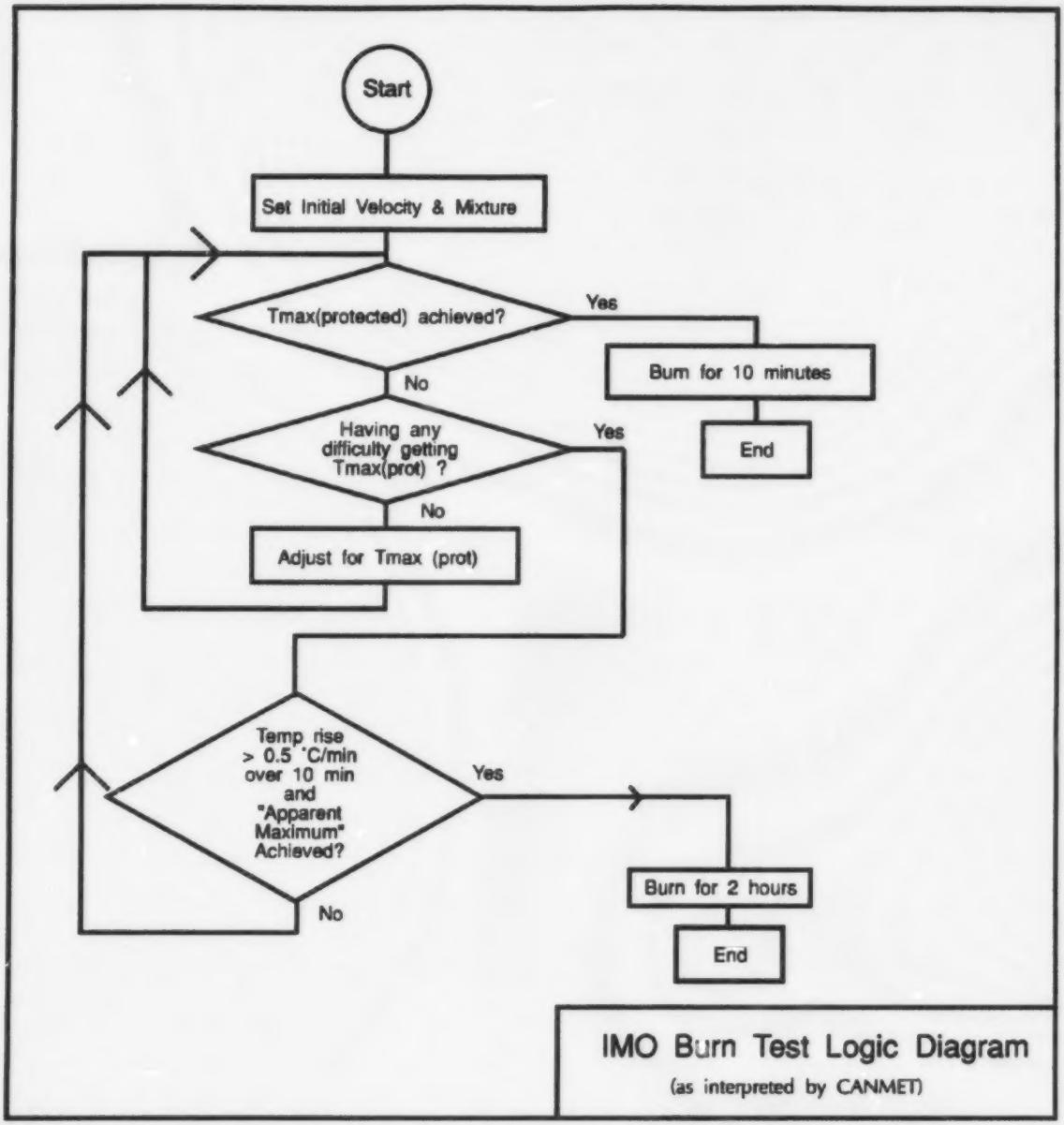

The first sentence of the above IMO requirements specifies that a specific gas concentration be used, namely the most easily ignitable mixture. There appears to be some conflict with subsequent sentences where the gas-air mixture is permitted to be varied. For the purposes of this discussion, the interpretation that mixture variation is permitted, will be used.

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The arguments as stated above in the USCG test discussion concerning maximization of temperatures on the protected side also hold for this discussion. The temperature on the protected side will vary little from ambient except at very low velocities, where some temperature rise can be obtained. There is no linkage connecting achievement of maximum temperature on the protected side with test conditions which could in any way ensure minimum times to flashback.

In the IMO standard, the observation of no temperature rise from ambient may be interpreted as a "maximum". There is no requirement in the IMO document that specifies some temperature rise should occur, whereas the USCG specifies a minimum rise of 100 °C (for detonation arresters only). All the IMO requires is a stabilization of temperature over a ten minute period; conceivably, this stabilization could be observed to occur at the room ambient level. Much of the work in Part A has shown that it is quite possible for the protected side temperature not to rise at all from the initial temperature. Since this can be interpreted as a "maximum" temperature when an IMO test is being carried out, the test could be concluded with a ten-minute burn under many circumstances.

If a low test velocity is chosen, it may be possible to demonstrate that a maximum temperature has been achieved, including some movement from room ambient temperature, in which case a short ten minute burn is again permitted to complete the test. The work in Part A of this report shows that these conditions are far from being worst-case conditions, and do not present a complete picture of the performance of the unit (see Figure 13, page 37).

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If a high velocity is chosen, there will likely be little or no upward movement on the protected side for at least ten minutes, and the unit could again qualify for a ten minute burn test.

If "difficulty" were encountered, a two-hour burn test could be conducted under any number of mixture and flow conditions that would produce a variety of performance times depending on the test conditions that were established, but probably not worst-case performance conditions. It would be difficult to determine when the "most severe apparent conditions" had been achieved, since variation of flow and mixture do not have an immediate effect on protected side temperature. It would also be difficult to interpret the phrase "apparent maximum" on an equatable basis.

There is again the implication that this test protocol involves one endurance burn test, with mixture and flow being varied during that one test. As discussed in the USCG section, it will be unlikely that the unique set of mixture and flow conditions that produce minimum time to flashback will be present for a significant period of time.

3.3 Conclusions

All the conclusions made with respect to the USCG requirements apply also to the IMO document:

- the IMO requirements have failed to determine the minimum time to flashback for a given unit;
- the performance capabilities of the flame arrester remain undetermined due to the unacceptably wide latitude for test conditions permitted by the IMO requirements.

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3.4 Recommendations

The necessity for a repeatable test as stated in the conclusions for the USCG requirements also holds true for the IMO requirements.

A series of tests for a flame arrester should be carried out under stoichiometric conditions, each at a fixed velocity. In this way, a determination of the minimum time to flashback for the flame arrester can be made. The range of test velocities used should be representative of velocities that would be encountered in most tanker vessel applications.

4. Underwriters' Laboratories Standard 525

4.1 Introduction

UL Standard 525 has been in effect for many years. It is intended for assessment of flame arresters being used as tank vents only.

The document requires that a stoichiometric (approximately) mixture of gasoline vapour and air be used for the fuel gas, and that a burn test be carried out at one specific velocity, related to the pipe size intended for connection to the unit.

4.2 Discussion of UL 525

Figure 2 (page 10) shows the time to flashback at the UL 525 test velocity for a crimped metal ribbon flame arrester. The UL 525 test provides an indication that the time to flashback would be on the order of one hour; comparison with times to flashback for other velocities for the same unit show just how incomplete a picture is provided when only one test at one velocity is conducted.

4.3 Conclusions

Although the UL 525 test has the same inadequacy as the other standards in that only one test is carried out and does not

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provide a complete picture about the performance of the unit, at least the test that is carried out is done on a more or less equatable basis. The test velocities that have been chosen for inclusion in the Standard must be representative of velocities encountered in actual applications.

From a testing point of view, there is little to be gained and much in the way of accuracy to be lost by using gasoline-air vapours for a test gas mixture, due to vaporization and condensation problems.

5. Draft Revision to UL 525 (dated October, 1991)

5.1 Introduction

At the time of writing this report, a draft revision of UL 525 was being circulated to interested parties. The document is much-expanded in that it takes into account flame arrester applications beyond tank vents. Endurance burn requirements are divided into separate parts for detonation arresters and deflagration arresters.

With reference to deflagration arresters, the user has the option of conducting burn tests either according to a method which parallels the IMO approach, or alternatively, the old UL 525 approach, described above.

With reference to detonation arresters, the user has the option of conducting burn tests in accordance with a procedure that largely parallels the USCG requirements for detonation arresters, or alternatively, in accordance with the old UL 525 approach except that the test is allowed to continue until flashback occurs.

5.2 Discussion - Deflagration Arrester Tests

Test Method No. 1 parallels the IMO requirements, except that no provisions are made for dealing with "difficulty" in obtaining

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maximum temperature on the protected side of the flame arrester. The testing authority is to vary mixture and flow conditions until the highest obtainable temperature on the protected side is reached, whereupon these conditions are to be maintained for ten minutes. After this, the flow is to be stopped and observations are to made for flashback.

This approach has the same inadequacies as the IMO approach, discussed above. If a sufficiently low velocity is chosen, there will be a gradual upward temperature trend on the protected side. There is a range of low velocities, all of which will produce a gradual climb in temperature on the protected side; whether or not flashback will occur within 10 minutes depends on the mixture concentration chosen.

There is again the implication that this test protocol involves one endurance burn test, with mixture and flow being varied during that one test. As discussed in the USCG section, it will be unlikely that the unique set of mixture and flow conditions that produce minimum time to flashback will be present for a significant period of time.

Endurance burn test method no. 2 is essentially the same as the existing UL 525 requirements, so the same discussion applies (see Part B, Section 4).

5.3 Discussion - Detonation Arrester Tests

Detonation arrester Endurance Burn Test No. 1 parallels the USCG burn requirements for detonation arresters, except that the two hour burn test has been eliminated, and all units are subject only to a ten minute burn test. The same general discussion as presented in the USCG section (Part B, Section 1) can be applied here.

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5.4 Conclusions

Conclusions stated in previous sections are equally applicable to the respective draft UL 525 endurance burn requirements.

In addition, the alternative test methods presented for both detonation and deflagration arresters cannot be considered equivalent because the latitude for setting USCG/IMO-style test conditions is so much greater than what is allowable in the old UL 525 requirements.

ACKNOWLEDGEMENT

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The authors also wish to acknowledge the cooperation of the manufacturers who supplied units for testing. Without these units, this report could not have been written.

REFERENCES

1. United States Federal Register, Volume 55, No. 120, dated June 21, 1990, Appendices A and B to Part 154.

2. International Maritime Organization document MSC/Circ.373/Rev.1 "Revised Standards for the Design, Testing and Locating of Devices to Prevent the Passage of Flame into Cargo Tanks in Tankers".

3. Underwriters' Laboratories document UL 525 "Flame Arresters for Use on Vents of Storage Tanks for Petroleum Oil and Gasoline".

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4. Underwriters' Laboratories draft proposal for a sixth edition of UL 525 dated October, 1991.

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